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Modelling the regional climate and isotopic composition of Svalbard precipitation using REMO_{iso}: a comparison with available GNIP and ice core data

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Abstract:

Simulations of a regional (approx. 50 km resolution) circulation model REMO_{iso} with embedded stable water isotope module covering the period 1958-2001 are compared with the two instrumental climate and four isotope series (δ^{18}O) from western Svalbard. We examine the data from ice cores drilled on Svalbard ice caps in 1997 (Lomonosovfonna, 1250 m asl) and 2005 (Holtedahlfonna, 1150 m asl) and the GNIP series from Ny-Ålesund and Isfjord Radio. The surface air temperature (SAT) and precipitation data from Longyearbyen and Ny-Ålesund are used to assess the skill of the model in reproducing the local climate. The model successfully captures the climate variations on the daily to multidecadal times scales although it tends to systematically underestimate the winter SAT. Analysis suggests that REMO_{iso} performs better at simulating isotope compositions of precipitation in the winter than summer. The simulated and measured Holtedahlfonna δ^{18}O series agree reasonably well, whereas no significant correlation has been observed between the modelled and measured Lomonosovfonna ice core isotopic series. It is shown that sporadic nature as well as variability in the amount inherent in precipitation process potentially limits the accuracy of the past SAT reconstruction from the ice core data. This effect in the study area is, however, diminished by the role of other factors controlling δ^{18}O in precipitation, most likely sea ice extent, which is directly related with the SAT anomalies. Copyright © 2011 John Wiley & Sons, Ltd.

KEY WORDS regional modelling; stable water isotopes; forward proxy modelling; Svalbard climate ice cores

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INTRODUCTION

The ability of general circulation models (GCMs) to simulate future climate scenarios is substantially constrained by the relative shortness and sparsity of available high quality instrumental climate data. It conditions the use of various climate proxy archives to reconstruct past climate variations and then to test and refine the existing climate models (Hegerl *et al*., 2006a,b).

Over the past few decades, ice cores proved to be a valuable source of proxy data for various climatic parameters of the past. The widely used method utilizes variations in the relative abundance of the stable water isotopes ^{18}O and ^{2}H(or D) as a proxy for the condensation temperature in the atmosphere at the time of precipitation (e.g. Jouzel and Merlivat, 1984; Ciais and Jouzel, 1994). The isotopic composition of a sample is generally expressed with the δ-notation defined as

$$\delta = \frac{R - R_{\text{SMOW}}}{R_{\text{SMOW}}} \times 1000‰$$

where R are the isotopic ratios of either [D]/[H] or [^{18}O]/[^{16}O], and R_{SMOW} is the isotopic Standard Mean Ocean Water (SMOW). The respective down-core variability of the δ^{18}O and δD parameters in the ice core can subsequently be translated into past surface air temperature changes. The approach has been applied in a number of studies involving ice core data from Antarctica (e.g. Jouzel *et al*., 1987a; EPICA Community Members, 2004; Jouzel, 2007), Greenland (e.g. North Greenland Ice Core Project Members, 2004) as well as outside major ice sheets (e.g. Eichler *et al*., 2009; Divine *et al*., 2011).

Such interpretation of the isotopic signal as a direct indicator of temperature often appears to be far too simplistic since the water stable isotopes in precipitation are integrated tracers of the water cycle (Alley and Cuffey, 2001). The values of δ^{18}O and δD in precipitation and their relationship with the ambient temperature depend on a number of additional factors such as variations in the

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moisture source region(s) (Boyle, 1997) or atmospheric processes causing isotopic fractionation en route. When interpreting the ice core series a potential for bias due to changes in precipitation seasonality (Cuffey *et al.*, 1995; Werner *et al.*, 2000; Krinner and Werner, 2003) have to be taken into account. On subannual time scales, the interpretation of the isotopic composition of the aggregate of individual accumulation events in terms of local temperature fluctuations can also be arguable (Helsen *et al.*, 2006). As a result, an empirical climate reconstruction (or inverse proxy modelling) relying implicitly on assumption of stationary δ^{18}O-SAT relationship has some inherent limitations and often may not be considered unambiguous.

The climate models fitted with stable water isotope diagnostics (e.g. Jouzel *et al.*, 1987b; Hoffmann *et al.*, 1998; Sturm *et al.*, 2005) may promote a better understanding of the features of the regional hydrological cycle. Such models can be used, for instance, to reveal the prevalent factors controlling the temporal and spatial variability of isotopes in local precipitation, supporting or rejecting the interpretation of an isotopic climate archive. Moreover, it makes it possible to directly compare model output with the measured isotopic data from a climate proxy archive. It implies that a prior reconstruction of climate variable(s) is not required, that is, the focus is shifted from 'inverse' to 'forward proxy modelling' (Sturm *et al.*, 2010).

However, as emphasized by Sturm *et al.* (2010), limitations inherent to climate models require that every such study involving climate simulations undergoes a thorough validation against observations for the study region. In the present work, we assess the performance of the regional circulation model $REMO_{iso}$ (Sturm *et al.*, 2005) with embedded stable water isotope module in simulation of Svalbard climate and elements of the local hydrological cycle. The regional (approx. 50 km resolution) model was forced at the lateral boundaries of the model domain by the global model $ECHAM_{iso}$ using the SST of the ERA-40 reanalysis for the period 1958–2001. This is the first attempt to model the regional climate and isotopic composition of precipitation in Svalbard with such spatial resolution. The lack of instrumental series from the study area conditions the model validation procedure based on a sitewise rather than gridded comparison of the modelled and observed data. We compare the model results with three isotope series from western Svalbard: two isotopic (δ^{18}O) records from ice cores drilled on Svalbard ice caps in 1997 (Lomonosovfonna, 1250 m asl) and 2005 (Holtedahlfonna, 1150 m asl) and two GNIP series from Ny-Ålesund and Isford Radio. Section 'Model setup' briefly presents the $REMO_{iso}$ climate model. Section 'Instrumental and Ice Core Data' describes the instrumental climate and isotopic data used for the model validation. The model's skill in reproducing the variability of local air temperature, precipitation amount and isotopic composition of precipitation are presented and discussed in Sections 'Modelled Variability of Precipitation and Air Temperature' and 'Performance of the Isotopic Module: A Comparison with the GNIP Data'. Section 'Modelling the Isotopic Records of Svalbard Ice Cores' shows the results of a simplistic modelling of the two Svalbard ice core records compared with the measured δ^{18}O series. The effect of sporadic nature of precipitation events and implications for interpretation of ice core δ^{18}O series in terms of past climate variations is analysed and discussed in Section 'Irregularity of the Snow Accumulation in Svalbard and Implications for Paleotemperature Reconstructions'. The results of the work are summarized in Section 'Conclusions'.

DATA AND METHODS

Model setup

$REMO_{iso}$ (REgionalMOdel) is a regional climate model having stable water isotope diagnostics ($H_2{}^{16}O$, $H_2{}^{18}O$ and $HD^{16}O$) embedded in the hydrological cycle (Sturm, 2005; Sturm *et al.*, 2005). The physics of $REMO_{iso}$ is based on ECHAM-4, with additional optimization for the Arctic regions by Semmler (2002). The updates for the Arctic include parameterizations of radiation, clouds, atmospheric liquid water, fractional sea ice, snow melt and refreezing, as well as initialization of ground moisture. The implementation of the isotope diagnostics in $REMO_{iso}$ was done in a similar fashion as for $ECHAM_{iso}$ (Hoffmann, 1995; Hoffmann *et al.*, 1998). Isotopic fractionation is accounted for all phase changes, including mixed-phase cloud processes and kinetic fractionation during snow formation. The sea ice cover, which plays an important role in forming the isotopic signal in Arctic precipitation, is parameterized from the driving SST fields using a threshold temperature of $-1{\cdot}77\,°C$ and interpolated to the $REMO_{iso}$ grid. The interpolation scheme allows a fractional sea ice cover to be calculated for individual grid nodes.

The model was set up in a rotated grid using the standard latitudinal and longitudinal resolution of $0{\cdot}5°$ ($\sim$55 km), 19 vertical layers and a time step of 5 min. At the lateral boundaries of the model domain (Figure 1), $REMO_{iso}$ received all prognostic variables from $ECHAM_{iso}$. Both models, $REMO_{iso}$ and $ECHAM_{iso}$, were forced with the 1959–2001 sea surface temperatures of the ERA-40 reanalysis product of the European Center of Medium-Range Weather Forecasts (ECMWF) (Uppala, 2005), and nudged to the ERA-40 wind fields to match the actual weather patterns, with spectral nudging being used for the regional model (Storch *et al.*, 2000). The model grid is centred on Greenland which was in the main focus of this numerical experiment (Sjolte, 2010). Despite that Svalbard is located in the north-eastern sector of the model domain, most of its area, including the sites used in the present model validation procedure, lie beyond the eight grid box ($\sim$400 km) buffer zone where the $REMO_{iso}$ precipitation is biased due to the assimilation of the ECHAM boundary conditions. The modelled data for the specified locations were obtained by linear

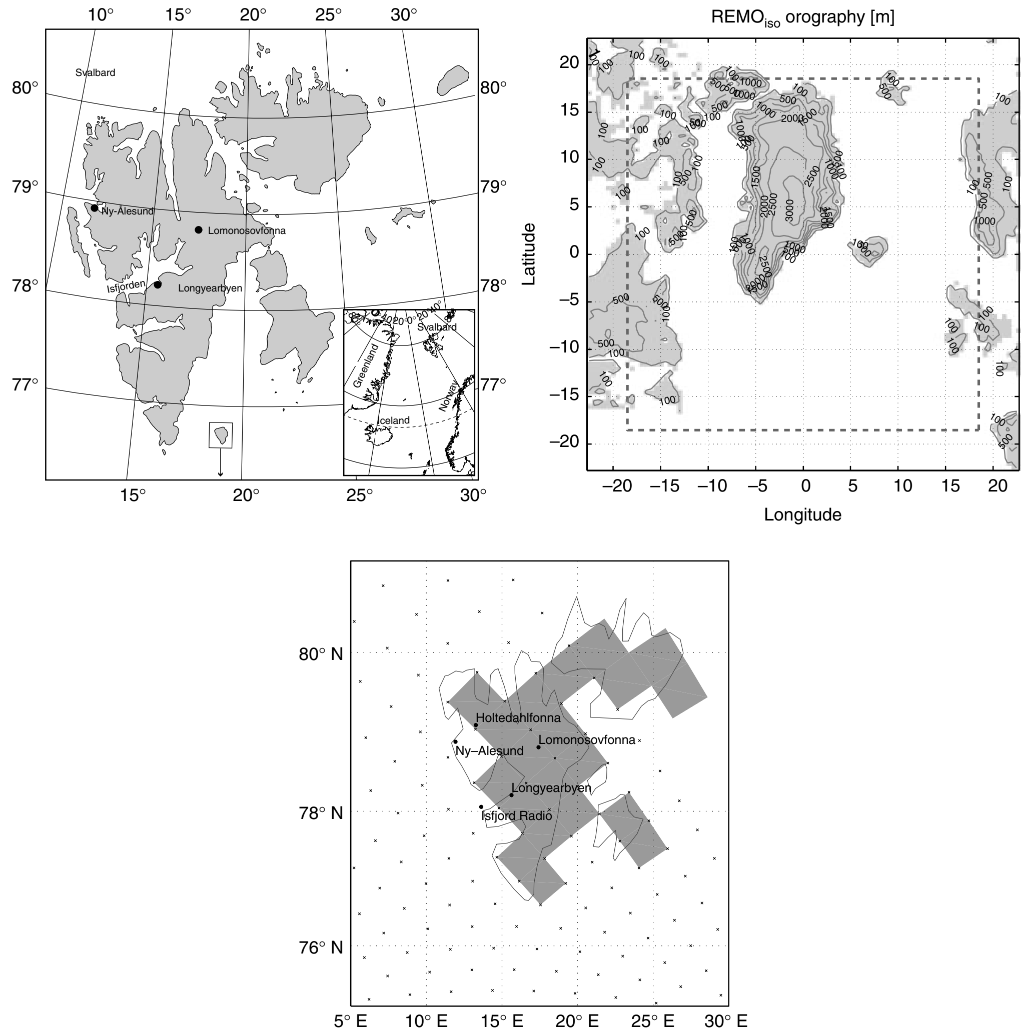

Figure 1. Upper left panel: Map of the study area showing the locations referred to in the text. Upper right panel: $REMO_{iso}$ model domain land–sea mask (shaded) and orography (contours) in rotated coordinates. Dashed box marks the domain boundary excluding the eight grid cell buffer zone where the regional model is relaxed towards the input field of the global model. Bottom panel: the model domain in Svalbard area excluding the eight grid cell buffer zone. Crosses show grid nodes with the land mask highlighted grey

interpolation of the model output from the adjacent grid nodes. A detailed description of the model setup as well as the experiment used in this study is also found in the study of Sjolte (2010).

Instrumental and ice core data

The model skills in reproducing the local climate variability are tested using the series of regular meteorological observations from the two locations in Svalbard: Longyearbyen (homogenized series available since 1917, data used since 1958) and Ny-Ålesund (data available since 1969). The results of the REMO isotopic module are compared with the available GNIP records of monthly mean $\delta^{18}O$ in precipitation from Svalbard stations Isfjord Radio and Ny-Ålesund (International Atomic Energy Agency/World Meteorological Organization, Global Network of Isotopes in Precipitation database, available at http://isohis.iaea.org). For the first record, spanning the period 1961–1976, the observations are rather irregular and the annual means can only be robustly estimated for 7 years. Ny-Ålesund, in contrast, has almost continuous series of monthly mean $\delta^{18}O$ in precipitation during 1990–2001 providing an overlap of 12 years in total between the model and the observations. The locations referred to in the text are indicated in Figure 1.

Longer continuous series of stable water isotopes in accumulated precipitation for the study area are stored in a number of ice cores drilled in Svalbard over the past few decades. In this work, we use two of them retrieved on the summit of Lomonosovfonna in 1997 at 1255 m asl (Isaksson, 2001; Kekonen *et al*., 2005) and Holtedahlfonna in 2005 at 1150 m asl (Sjögren *et al*., 2007). Accurate chronologies for the cores were established using a combination of dated reference layers, such as the 1963 ^{137}Cs peak and volcanic eruptions, annual cycles of water isotopes and glaciological modelling (Pohjola *et al*., 2002a; Kekonen *et al*., 2005). The average sampling resolution within the interval of overlap with the model data is about 10 and 12 samples a year for the Lomonosovfonna and Holtedahlfonna cores, respectively. For about 10% of the samples, a replicate analysis on $\delta^{18}O$ content was carried out with an overall reproducibility better than ±0·1‰.

Table I. Coordinates and altitude for locations referred to in the text

	Longyearbyen	Isfjord Radio	Ny-Ålesund	Lomonosovfonna	Holtedahlfonna
Coordinates	78°13′*N*,15°37′*E*	78°4′*N*,13°38′*E*	78°55′*N*,11°56′*E*	78°51′*N*,17°25′*E*	79°13′*N*,13°27′*E*
Altitude, m asl	38 (224)	<10 (120)	<10 (235)	1250 (590)	1150 (569)

Values inside parentheses designate the altitudes of the sites in the 'model world'.

For the considered period the dating accuracy is estimated to be within 2 years. Isaksson (2001) and Divine *et al.* (2008) provided more details on the Lomonosovfonna ice core analysis; a thorough discussion of the water isotopes in relation to melt features was presented by Pohjola *et al.* (2002b). The geographical coordinates of the locations considered in the present study are summarized in Table I.

RESULTS AND DISCUSSION

Modelled variability of precipitation and air temperature

Figure 2 demonstrates that the seasonal cycle in Longyearbyen and Ny-Ålesund calculated from daily means in the analysed environmental parameters is reasonably well captured by the model. However, the model tends to produce a systematic cold bias in the estimated winter SAT of the order of 7 °C for February mean. The cold bias found in the simulation suggests that the model overestimates the strength of winter inversion in the atmospheric boundary layer for the specified sites. This can be attributed to the spatial resolution of the model which is not yet sufficient to capture a specific coastal location of both settlements, with proximity of open water areas even during winter months. A continental effect of more inland location of Longyearbyen in the model, compared with Ny-Ålesund (Figure 1), also explains a warm bias of about 2–3 °C in the modelled SAT during summer months.

The SAT variability itself at monthly time scales and longer is reproduced rather well, as indicated by the correlation coefficient of the order of 0·9 between the observations and the modelling results (Figure 2). When the annual cycle is removed and both the modelled and observed monthly series are converted into anomalies, the correlation decreases to still fairly high value of 0·85.

Instrumental data on precipitation is traditionally reproduced relatively poor in the model when compared with air temperatures. This is not least because of a higher, compared with the SAT, spatial variability in the amount of precipitation as well as objective difficulties associated with an accurate instrumental measuring of this parameter. The latter is known to be of particular relevance in the winter Arctic conditions (Hanssen-Bauer *et al.*, 1996). Nevertheless, Table II suggests a reasonably good agreement between the model and observations in terms of multiannual mean precipitation totals. A weakly pronounced annual cycle in precipitation from Ny-Ålesund, with the winter maximum and summer minimum, is also accurately captured by the model. The correlation of the order of 0·5 between the modelled and measured monthly precipitation is slightly higher for the winter series.

For Longyearbyen the agreement between the model and the instrumental data on precipitation amount is much poorer, with a substantial overestimation of the precipitation in the model being the most prominent feature (Figure 2h). The reason to such a discrepancy is not quite clear. Since for the four of five locations considered in the present study no significant bias in the precipitation amount was revealed (Table II) it is probably related to the effect of the local orographic features on local precipitation in Svalbard airport, not taken into account in a relatively coarse model domain.

Performance of the isotopic module: a comparison with the GNIP data

Figure 3 demonstrates that the REMO isotopic module tends to overestimate the summer δ^{18}O values in Ny-Ålesund precipitation, yielding a pronounced seasonal cycle that is not obvious in the instrumental GNIP data. The winter isotopic signature is correspondingly slightly biased towards more negative, 'isotopically colder', values. The annual mean δ^{18}O in Ny-Ålesund inferred from the 12-year period of overlap between the model and GNIP data are, however, very similar (Table II). In general, REMO$_{iso}$ shows a better performance during winter. The overall correlation of 0·40 between the modelled and observed monthly mean δ^{18}O in precipitation (Figure 3c) increases to 0·64 when April–October months are left out.

Figure 4 compares modelled δ^{18}O in monthly precipitation with the more sparse GNIP series from the Isfjord Radio station in Svalbard. Being a coastal site, Isfjord Radio same as Ny-Ålesund, is situated in proximity of the open water during a substantial part of the year. Despite the model in a much the same way yields the negative bias in the estimated monthly mean δ^{18}O, the seasonal cycle in δ^{18}O is still more pronounced in the Isfjord Radio data. One should point out, however, that the climate conditions during the considered periods were essentially different. Compared with generally warmer 1990s, the period of 1960s–1970s was cold in Svalbard. The November–March mean temperatures were some 4 °C lower on average. A preferentially negative NAO during 1961–1976 (Hurrell and van Loon, 1997) would potentially implied a diminished activity of Arctic cyclones in the study area in winter accompanied by a southerly displacement of cyclogenetic areas (Zhang *et al.*, 2004). Longer distillation routes result, in turn, in greater depletion for heavier isotopes in the moisture

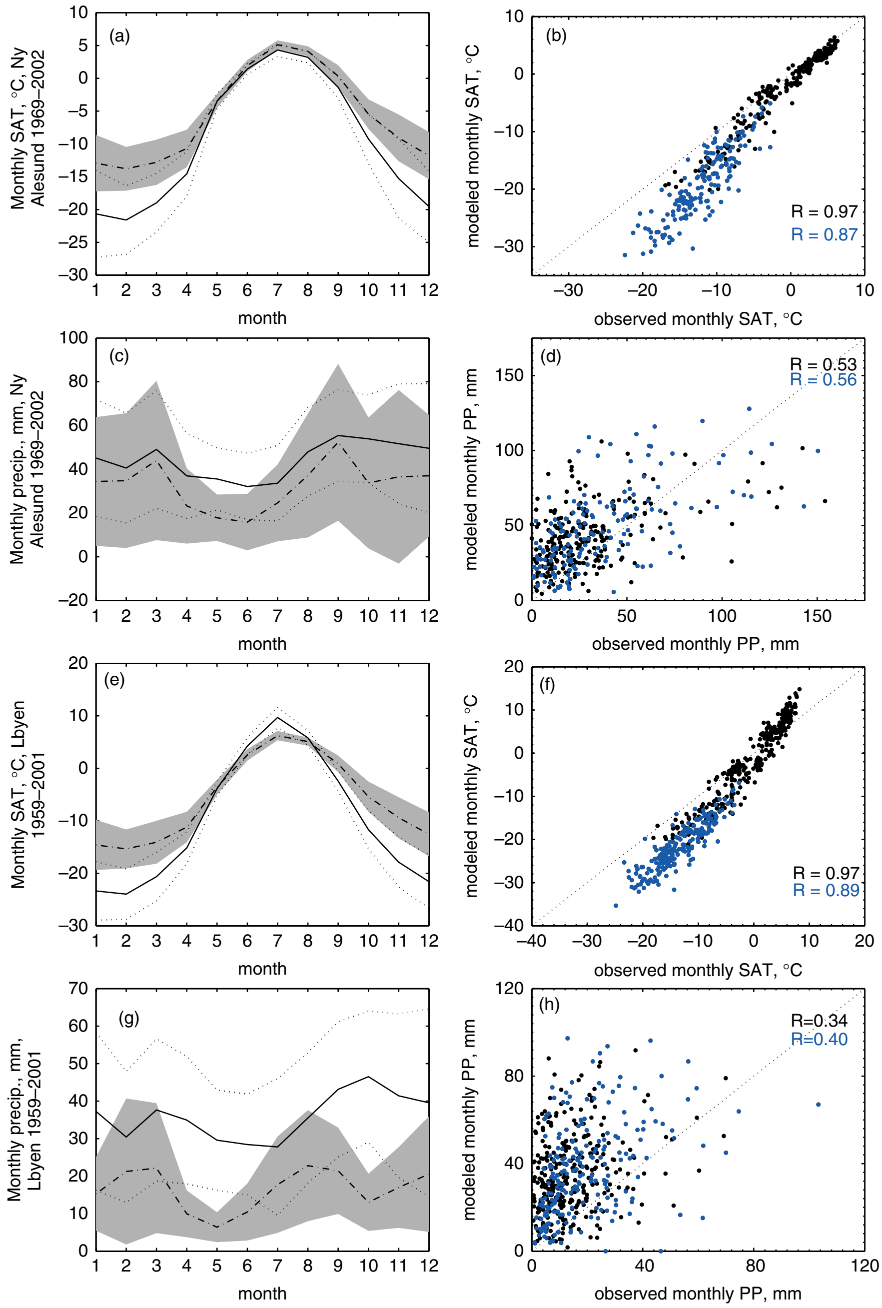

Figure 2. Ny-Ålesund observed (shaded and dash-dotted) and simulated (full line and dotted) mean annual cycle for SAT (a) and precipitation (c) in the period 1961–2001 with one standard deviation indicated. The correspondent scatter plots are shown in panels (b) and (d) with winter (November–March) values highlighted blue. Numbers indicate the correlation coefficients between the observations and the model. Panels (e–h) show the same but for Longyearbyen for the period 1959–2001

Table II. Multiannual mean precipitation totals (PP) and δ^{18}O in accumulated precipitation for the four locations in Svalbard

	Isfjord Radio (1961–1975)	Ny-Ålesund (1990–2001)	Lomonosovfonna (1959–1996)	Holtedahlfonna (1959–2001)
$\delta^{18}O$,	−9·7	−11·8 (0·7)	−16·0 (0·9)	−14·2 (0·6)
‰(std)	*−13·9*	*−13·8 (0·7)*	*−15·8 (0·9)*	*−15·4 (1·0)*
PP; λ,	0·47(0·11)	0·43(0·11)	0·39(0·12)	0·52
m/year(std)	*0·40 (0·08)*	*0·55 (0·06)*	*0·43 (0·1)*	*0·42 (0·08)*

For the GNIP data the annual δ^{18}O are estimated by simple averaging of the respective monthly means, while for the ice core sites the annual values are based on averaging of the precipitation-weighted monthly means. Note that for the ice core locations the accumulation λ (i.e. $P-E$ parameter in the model) is used instead of the precipitation totals. The period for averaging corresponds to the period of overlap between the model and the instrumental data. Italics is for the same parameters but in the 'model world'. Numbers in parentheses indicate the respective standard deviations estimated using the annual means. Due to less regular observations the standard deviations were not calculated for Isfjord Radio series.

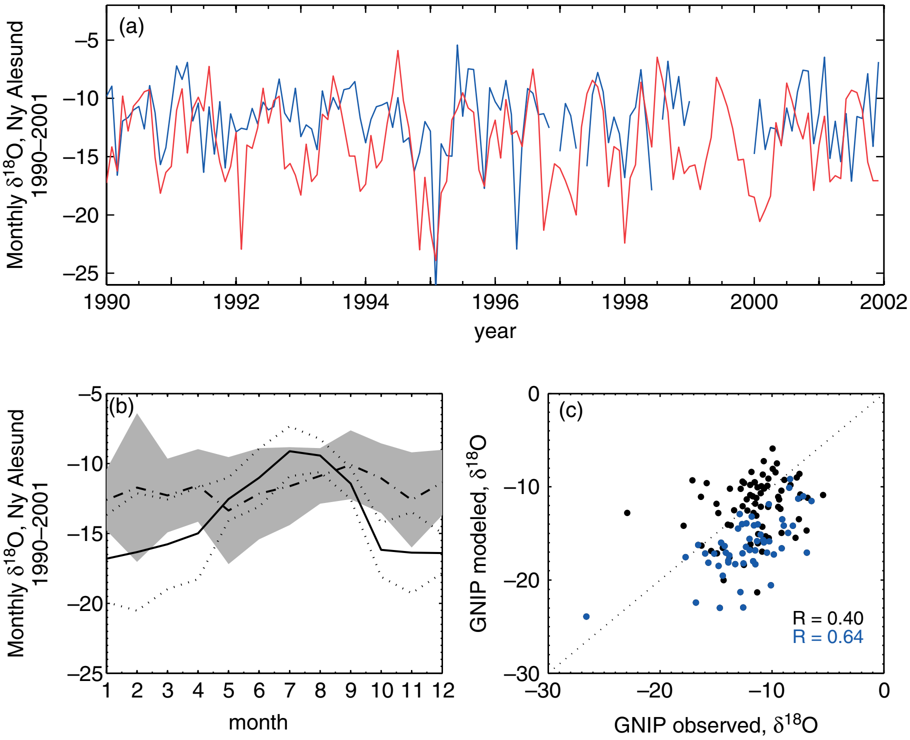

Figure 3. (a): Ny-Ålesund observed (blue, GNIP data) and simulated (red) δ^{18}O in monthly precipitation for the period 1990-2001; (b) Ny-Ålesund observed (shaded and dash-dotted) and simulated (full line and dotted) mean annual cycle for δ^{18}O in monthly precipitation; (c) data from panel (a) shown as a scatter plot, with winter values highlighted blue. Numbers indicate the correlation coefficients between the observations and the model

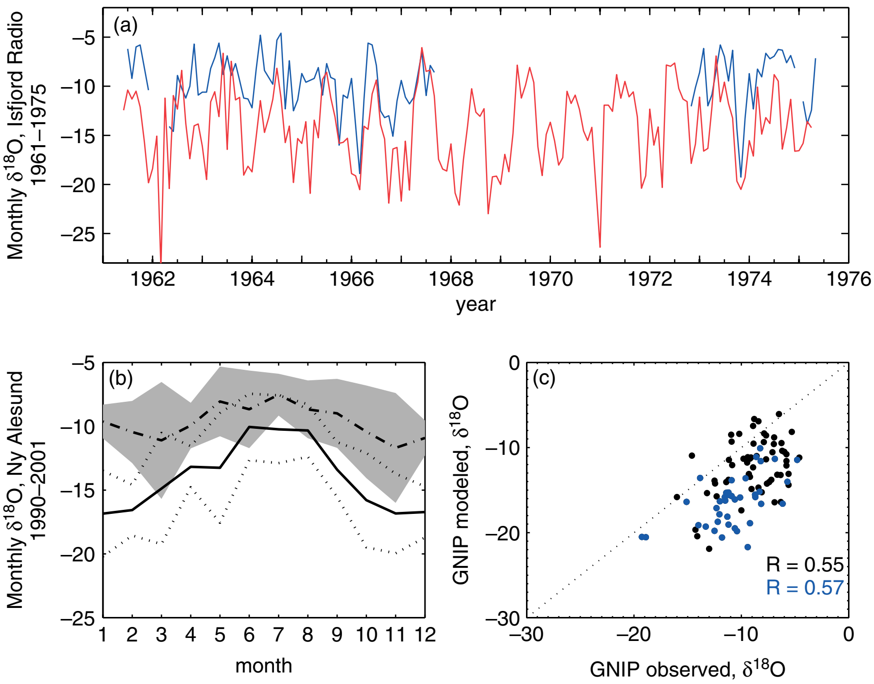

Figure 4. Same as in Figure 3 but for Isfjord Radio station GNIP data for the period 1961–1975

transported to Svalbard. Generally larger winter sea ice extent in the Nordic Seas during this time-period (Vinje, 2001; Divine and Dick, 2006) could amplify the isotopic distillation over the ice covered areas, hindering the isotopic enrichment of water vapour in the advecting air parcel by entrainment of local, less isotopically depleted moisture (Noone and Simmonds, 2004).

Assessment of isotopes to climate relationship from the model data yields the values of the slope between the annual mean δ^{18}O and SAT to be within 0·4–0·5 (‰/°C) for the five locations considered. For Ny-Ålesund with the only nearly continuous instrumental (non-ice core) δ^{18}O series, the respective annual mean based estimate is 0·42 (0·23)(‰/°C) which is much in line with the

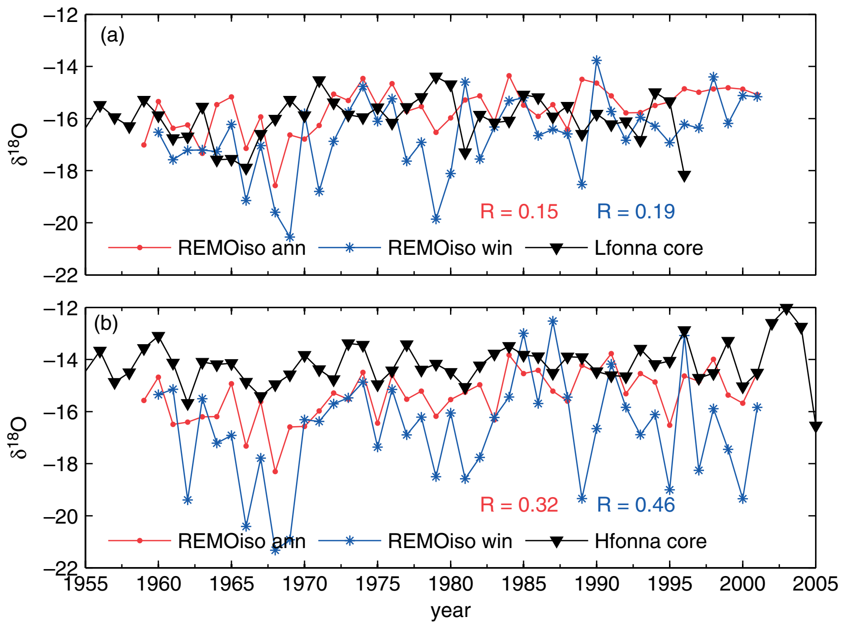

Figure 5. Modelled Lomonosovfonna (a) and Holtedahlfonna (b) accumulation weighted annual and November–March δ^{18}O series (red, circles and blue, asterisks) compared with the observed ice core data (black lines, triangles)

model-based estimate of 0·48(0·06) (‰/°C) made for this location.

Modelling the isotopic records of Svalbard ice cores

The model elevation for the ice core sites is below 600 m. Figure 5 and Table II, however, suggest that modelled and measured multiannual mean δ^{18}O values agree quite well. Given the tendency of REMO$_{iso}$ to overestimate the isotopic distillation during winter and stronger ablation of isotopically enriched accumulated precipitation during summer, this would be indicative of the relative role of altitudinal effect on mean δ^{18}O in precipitation in the study area.

Figure 5 depicts the modelled δ^{18}O in the analysed ice cores and compares them with the measured profiles. We note that the processes responsible for post-depositional alterations of the initially deposited profiles, like water vapour diffusion in the snow pack or percolation due to summer melt are not here taken into account (Pohjola *et al.*, 2002b; Grinsted *et al.*, 2006). The timescale errors typically inherent to proxy data may also compromise a potential agreement between the model and the real data on the year-to-year basis. Nevertheless, the results demonstrate that interannual variability is reproduced fairly well for the Holtedahlfonna ice core data. Despite the numerous uncertainties associated with comparison of the model and instrumental data, the series show weak but essentially positive statistically significant correlation of 0·32. The correlation increases to 0·46 when the modelled winter values only are considered. Diminished variance during the period of overlap, 0·38 *versus* 0·93‰^{2}, in the measured δ^{18}O profiles compared with the model results signifies the effect of post-depositional alterations occurring in the accumulated snowpack. A higher correlation with the winter values is due to the following factors. Comparison with the GNIP data suggests that the isotopic signature of winter precipitation is better reproduced in REMO$_{iso}$. Besides, the winter months contributes most to the overall interannual variability in the air temperatures as well as δ^{18}O in precipitation (Divine *et al.*, 2011).

In contrast to Holtedahlfonna, the Lomonosovfonna δ^{18}O series shows no statistically significant correlation with the modelled data. With the lack of *in situ* high-resolution instrumental data, the reasons for such discrepancy remain speculative. The poor year-to-year agreement could be, for example, due to a higher contribution of precipitation at the core site formed by the easterlies, implying possible boundary effects between the much coarser ECHAM and the regional REMO$_{iso}$ grids. The wind erosion of the snow pack on the exposed summit of Lomonosovfonna represents another potential source of random bias (Fisher *et al.*, 1985). We note that the modelled and the ice core-based annual mean snow accumulation estimates are in very good agreement (Table II). While the longer term means are similar, the wind-driven noise at deposition may however cause misidentification of the annual layers in the raw ice core record during the core dating procedure. The effects of summer melt and percolation altering the initial δ^{18}O stratigraphy are also potentially stronger at the Lomonosovfonna ice core site due to a lower annual accumulation rate there (Table II). Notably, a very simplistic modelling of the percolation by calculation of forward biannual δ^{18}O means weighted by annual accumulation and accompanied by a one year-shift of the derived series substantially increases the correlation with the ice core δ^{18}O series to a value of 0·43. The need to shift the series, in turn, can be indicative of a systematic error in the core timescale.

Table III summarizes the linear trend magnitudes calculated for the isotopic series, both modelled and

Table III. Magnitudes of linear trends in the time series of annual mean SAT (Longyearbyen, Ny-Ålesund) and $\delta^{18}O$ (Lomonosovfonna, Holtedahlfonna)

	Observed	Modelled
Longyearbyen		
1959–1996	0·04(0·02)*	0·05(0·02)*
1959–2001	0·05(0·02)*	0·06(0·02)*
Lomonosovfonna		
1959–1996	0·01(0·01)	0·03(0·01)*
1959–2001		0·03(0·01)*
Ny-Ålesund		
1969–2001	0·03(0·02)	0·1(0·04)*
Holtedahlfonna		
1969–2001	0·00(0·01)	0·02(0·01)*
1959–2001	0·00(0·01)	0·03(0·01)*

The periods used for trend estimates correspond to the periods of overlap between the model and the instrumental data. Units are in °C/year (SAT) and ‰/year ($\delta^{18}O$). Standard deviations of the slopes are shown in parentheses. Asterisks mark the trends that are statistically significant at the 95% confidence level according to the *t*-test.

observed. The estimates of the trend slopes are also compared with the available instrumental SAT records from Ny-Ålesund and Longyearbyen during the respective periods of overlap. The model accurately captures the tendency towards warmer climate in Svalbard during the recent few decades. The corresponding trends in the isotopic series appear to be statistically significant in the modelled data only. Yet the overlapping 2σ confidence intervals for the slopes estimated from the modelled and measured Holtedahlfonna and Lomonosovfonna ice core $\delta^{18}O$ series indicate that this difference should be considered as insignificant.

We note that such a comparison is generally not unambiguous due to the simplified approach to modelling the isotopic profiles in the ice cores used in the present study. Depending on snow accumulation at the core site, the isotopic diffusion in the snow pack and firn may substantially modify an initially deposited profile of $\delta^{18}O$ (Fisher *et al.*, 1985; Johnsen *et al.*, 2000; Helsen *et al.*, 2006). Since the diffusion process is continuous through time, the deeper layers will be altered to a greater extent than the uppermost ones.

The lack of sensitivity to the SAT changes in the $\delta^{18}O$ ice core records at the interannual to decadal scale seems to undermine the concept of a partial temperature control on $\delta^{18}O$ in precipitation in Svalbard. One should, however, point out again a substantial difference in the geographical settings between the considered locations. In contrast to the meteorological stations situated approximately at the sea level, the ice cores were retrieved from the exposed higher altitude sites on the summits of the glaciers. The complex surface topography affecting the air flow, together with the low-level temperature inversions typically occurring during winter under clear-sky conditions, tend to decouple the air temperature evolution between the sites. The irregularity of precipitation events also suggests that the direct comparison of the instrumental and ice core series should generally be done with a caution. This fact is accounted further in next subsection

Irregularity of the snow accumulation in Svalbard and implications for paleotemperature reconstructions

In Svalbard precipitation events are often associated with a passage of Arctic cyclones which represents one of the principal mechanisms for the transport of heat and moisture into the polar regions. During the winter, the southerly advection of relatively warm air together with decay of the low-level temperature inversion layer causes the air temperature near the surface to increase. Therefore, the days with intense precipitation events in Svalbard in the winter tend to be warmer on average. At the same time, the summer Arctic cyclones do not exert a similar influence on Svalbard summer surface air temperatures as the cyclogenesis area migrates to the north of the Eurasian coast and the North Atlantic storm track is weakened (Serreze, 1995).

Both the instrumental and the model data demonstrate the irregularity and variations in intensity of precipitation events in the study area. In order to assess the magnitude of this effect on the annual time scale, we estimated the mean annual temperatures for the days with precipitation. A threshold of 0·5 mm/day was set to eliminate days when only traces of precipitation fell. Furthermore, to investigate the possible implication of variations in the amounts of precipitation for paleotemperature reconstructions from Svalbard ice cores, we calculated the annual mean precipitation-weighted surface air temperatures.

Figure 6 demonstrates the results of the analysis indicating the presence of a pronounced warm bias in the precipitation-weighted annual SAT. The magnitude of the bias varies with time, being of the order of 2·3 °C and 2·5 °C in the Longyearbyen and Ny-Ålesund instrumental data, respectively (ca. 4 °C in REMO$_{iso}$). The bias is strongest during winter (Figure 7), in agreement with the effect of advection of heat and strengthened turbulent mixing in the surface layer during the cyclone passage. Notable also is a weak, of the order of 1 °C, cold bias in the mean precipitation-weighted July air temperatures. The latter is most likely due to less incoming shortwave radiation during the cloudy days associated with precipitation events.

More important is that the precipitation-weighted SAT shows different temporal variability than the raw SAT series. As suggested by Figure 6, the correlation coefficients between the mean annual SAT and precipitation-weighted mean annual SAT are of the order of 0·5–0·6 both for the instrumental and the model data. Such discrepancy may potentially place a natural limit on the accuracy of the past SAT reconstruction derived from an isotopic paleoclimate archive (Sturm *et al.*, 2010). If the $\delta^{18}O$ to SAT relationship during precipitation was perfectly linear and stationary in time, the direct interpretation of the isotopic records for this area in terms of the ambient temperature would allow us to capture some 40% of the variance at best. In reality the assumption of linearity does not hold for all regions and time scales. It

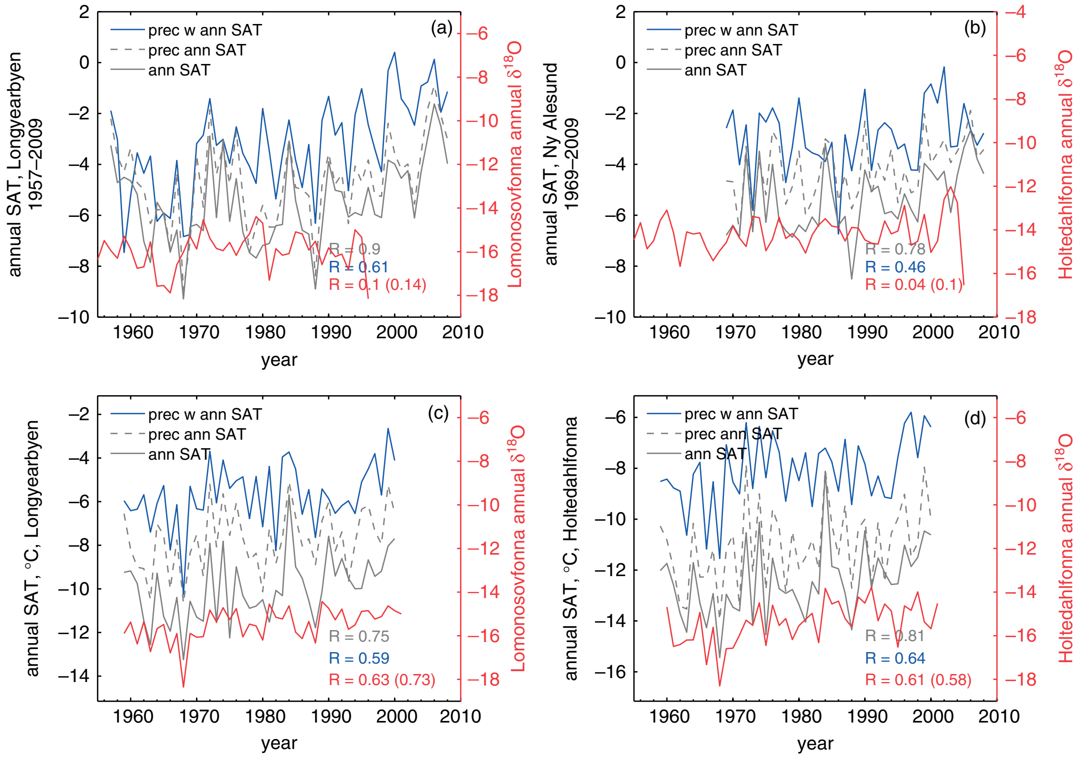

Figure 6. (a, c) Longyearbyen observed and simulated annual mean SAT (solid grey), mean SAT for days with precipitation (dashed grey) and precipitation-weighted SAT (blue). (b and d) Same as in (a and c) but for Ny-Ålesund observed and Holtedahlfonna simulated SAT. Grey (blue) numbers indicate the correlation coefficients between the mean SAT for days with precipitation (precipitation-weighted SAT) and the annual mean SAT. Red lines show the observed and simulated annual mean δ^{18}O series for Lomonosovfonna (a, c) and Holtedahlfonna (b, d) with numbers highlighted red for the correlation coefficients between the annual mean δ^{18}O and SAT (precipitation-weighted SAT given in parenthesis, respectively)

has been revealed that the local δ^{18}O/SAT slope may vary in response to changes in such controlling factors as water vapour source area (Boyle, 1997; Jouzel, 1997; Cuffey and Vimeux, 2001), distillation history of the air mass en route (Kavanaugh and Cuffey, 2003) or microphysical processes in clouds during snow formation (Ciais and Jouzel, 1994). Furthermore, the initially deposited profiles of δ^{18}O are subject to various post-depositional alterations (Pohjola *et al.*, 2002b; Grinsted *et al.*, 2006) and dating uncertainties. It implies that the anticipated correlation between the annual mean SAT and the ice core δ^{18}O should even be lower. This inference is, however, explicit with the ambient temperature being the principal controlling factor on the isotopic composition of precipitation. For such locations, the precipitation-weighted SAT will indeed be a better target for paleoclimate reconstructions.

Comparison of the simulated annual mean δ^{18}O series with the modelled Holtedahlfonna and Longyearbyen air temperatures yields correlation coefficients of a similar magnitude for both SAT and precipitation-weighted SAT (Figure 6c and d). Moreover, the derived correlations are of the same order as the ones found between the SAT and precipitation-weighted SAT. This is indicative of the role of other factor(s), most likely sea ice extent variations, affecting the isotopic composition of precipitation and directly related namely with the ambient air temperatures. The latter is supported by prominent air temperature–sea ice link established for Svalbard climate (Benestad *et al.*, 2002), as well as the known effects of sea ice on the distillation history of an air mass and hence δ^{18}O in precipitation (Noone and Simmonds, 2004). This connection between the Lomonosovfonna δ^{18}O and sea ice extent in the study area has recently been used in paleoreconstruction of past sea ice variations in the Nordic Seas (Macias Fauria *et al.*, 2010).

The correspondent values for the instrumental data (see Figure 6a,b) on interannual scales are virtually indistinguishable from zero. However, as shown by Grinsted *et al.* (2006) and Divine *et al.* (2011), smoothing by a 5-year running mean, together with the use of winter (DJF) instead of the annual mean SAT increases the correlation between the Lomonosovfonna δ^{18}O and instrumental SAT to a value of about 0·5. This inferred relationship with winter SAT was used to reconstruct past winter temperature variations in Svalbard and northern Norway back to approximately 800 AD (Divine *et al.*, 2011).

CONCLUSIONS

The stable water isotopes from various climate archives are known to contain an abundance of climate information. Their interpretation is often not trivial since both δ^{18}O and δD in precipitation are integrated tracers of the water cycle and influenced by a wide range of climate-related processes. Climate models with embedded stable water isotope diagnostics can aid in disentangling the contributions from different processes into the

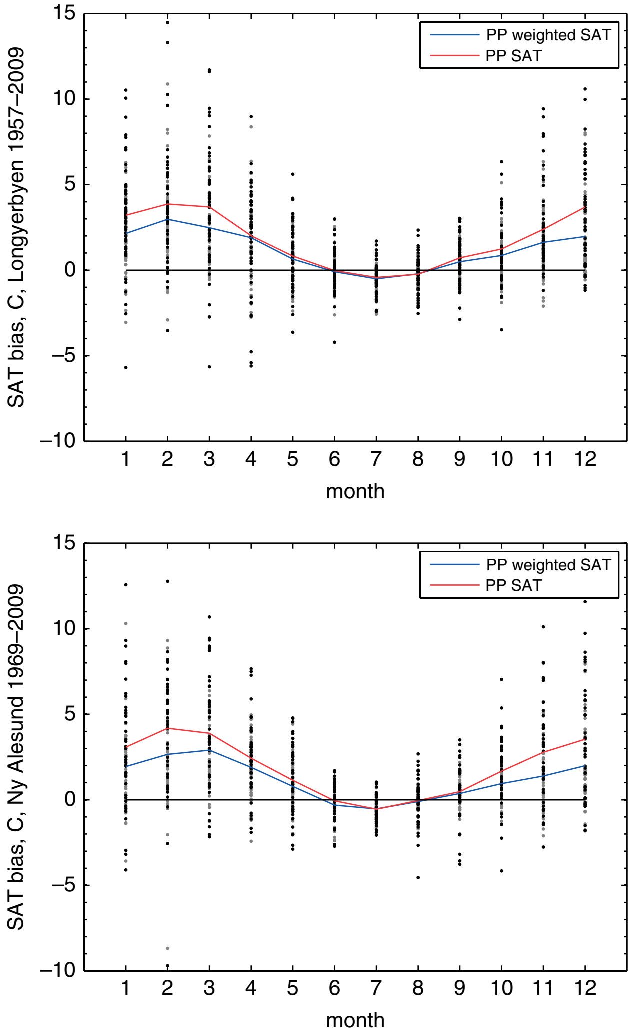

Figure 7. Observed bias in the mean monthly SAT for the days with precipitation and for the days with precipitation, weighted by daily accumulation in Longyearbyen (a) and Ny-Ålesund (b), as estimated relative to the mean monthly SAT

final isotopic composition of precipitation. It, however, requires the simulations of climate and hydrological cycle to undergo a thorough evaluation against observations for the considered region.

The presented study assessed the skill of a regional circulation model REMO$_{iso}$ with embedded stable water isotope module in simulation of Svalbard climate and elements of the local hydrological cycle for the period 1959–2001. For the validation procedure, we employed two instrumental climate series from local meteorological stations and four δ^{18}O isotope series from western Svalbard: two from the ice cores and two from the GNIP archive. Model demonstrated a good performance in capturing present climate variations on the daily to multidecadal times scales, yet producing a cold bias of the order of 7 °C in the winter SAT. Comparison of the observed and modelled precipitation for the two locations in Svalbard has revealed generally worse agreement than for the surface air temperature. The modelled mean annual precipitation totals for Longyearbyen are higher by a factor two on average than was actually measured during 1959–2001. The precipitation in Ny-Ålesund, nevertheless, has been more accurately reproduced by the model. One should also remember that the quality of the precipitation observations themselves can be a factor for the evaluation of the model skill. Additional uncertainties stem from a simplified model orography that does not account for the smaller scale topographic features crucial for the spatial variability in precipitation. In support of the model performance, the multidecadal mean values of accumulation inferred from the ice cores and modelled by REMO$_{iso}$ were found to be fairly close.

Comparison of the GNIP data from Ny-Ålesund with the model output has shown that the isotopic module of REMO$_{iso}$ simulates reasonably well the winter isotopic composition of precipitation in Svalbard ($R = 0{\cdot}64$), with some less accurate performance during summer. A negative bias in winter and positive in summer δ^{18}O of the order of 1–4‰leads to the overestimated seasonal amplitude of this stable water isotope. A simplistic modelling of the ice core records yielded the results that are in partial agreement with the observed δ^{18}O series from Lomonosovfonna and Holtedahlfonna cores. For both cores, the observed and simulated multidecadal means δ^{18}O lie within the 1-σ interval of error. The interannual variability is reproduced fairly well for the Holtedahlfonna ice core data as demonstrates the correlation of 0·32, which increases to 0·46 when the winter values only are considered. No significant correlation was found between the simulated and observed Lomonosovfonna δ^{18}O series. There are hints, however, to the effects of summer melt and percolation as well as the timescale errors, responsible for the lack of agreement between the modelled and the instrumental data. We note therefore that a more accurate comparison of the modelled and measured from ice cores δ^{18}O requires the effect of post-depositional alterations of stable water isotopes in the accumulated snow pack to be taken into account. This can be implemented via back-diffusion of the instrumental ice core δ^{18}O or forward modelling of the ice core records by diffusion of the simulated initial δ^{18}O profiles (Bolzan and Pohjola, 2000; Helsen *et al.*, 2006).

These preliminary results encourage a further use and analysis of the REMO$_{iso}$ data. We believe that the model can successfully be used to improve our understanding of the processes driving the variability of water isotopes in Svalbard precipitation at the broad range of time scales. This includes the effects of regional sea ice extent variability, changing atmospheric circulation patterns associated with precipitation events as well as changes in seasonality of precipitation. Disentangling the influence of variable contribution of moisture from different sources to the overall moisture budget and the correspondent impact on $\delta^{18}O$/dD of precipitation at a specific site would, however, require a combination of the model data with Lagrangian moisture diagnostic (e.g. Sodemann *et al.*, 2008). Assessment of the synergetic effect of these processes on the longer time scales has a particular importance in terms of interpretation of past stable water isotopes in precipitation recorded in ice cores. This will boost the accuracy of ice core-based climate reconstructions for Svalbard.

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